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CONTINEX: A Toolbox for Continuation in Experiments

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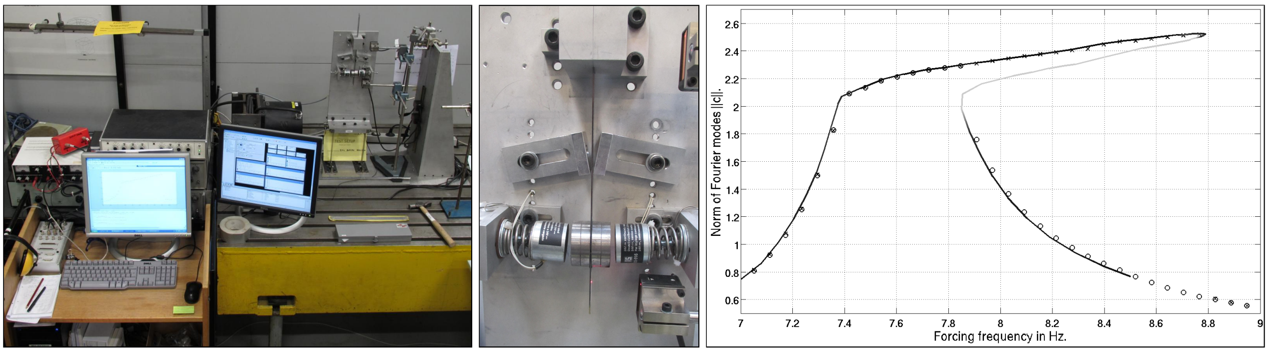
Summary. CONTINEX is a MATLAB toolbox for bifurcation analysis based on the development platform COCO (computational continuation core). CONTINEX is specifically designed for coupling to experimental test specimen via DSPACE, but provides also interfaces to SIMULINK-, ODE-, and so-called equation-free models. The current version of the interface for experimental set-ups implements an algorithm for tuning control parameters, a robust noise-tolerant covering algorithm, and functions for monitoring (in)stability. In this talk we will report on experiments with an impact oscillator with magnetic actuators and algorithmic challenges we were facing during toolbox development.



(a) Top view of test rig. (b) Oscillator. (c) Bifurcation diagram with stability indicated.

Figure 1: An impact oscillator experiment (a) and (b), and its bifurcation diagram (c) obtained with a recent version of CONTINEX [1, 2]. The results of an up- (×) and down-sweep (○) are shown in the background for comparison. Our current version of CONTINEX is able to follow branches of unstable responses as well as assess the stability of responses during continuation.

Introduction

The goal of this development effort is a robust continuation toolbox that can be coupled to test specimen in a lab and runs without or with only minimal supervision, thus allowing unattended execution of sequences of continuation runs for extensive data acquisition. Furthermore, a well equipped toolbox will provide means for monitoring stability properties along the solution manifold, and for branch-switching at bifurcation points. The current version of the toolbox CONTINEX implements a fully functional covering algorithm as well as several monitor functions to detect instability of a solution. Hence, it provides basic means for the location of bifurcation points during continuation. The classification of such points and methods for branch-switching are subjects of ongoing research.

CONTINEX is based on the computational continuation core COCO [3], which implements a fully developed continuation toolbox and allows for easy overloading of specific parts of its continuation algorithms. For our development we only wish to overload a minimal amount of functionality, necessitated by particularities of continuation in experiments [4, 5, 6]. One such particularity is the uncertainty of measurements, which implies that a solution manifold can only be defined in terms of expected values, if at all. Other significant particularities are addressed in the next section.

For developing and testing CONTINEX we set up the simple impact oscillator experiment shown in Figure 1, which consists of a flexible vertical beam with a tip mass attached at the lower end. The beam is clamped and horizontally excited with an electromagnetic shaker at the upper end and impacts mechanical stops if the relative deviation of the tip mass exceeds a certain value. Such an impact causes an increase of stiffness, resulting in a non-linear mass-spring-damper system with stiffening spring. Although the oscillator was designed as a one degree of freedom system, the actual set up exhibits phenomena typical for two degree of freedom systems, that is, vibration suppression and resonances with the shaker.

Our experiment serves as a prototype for rotating machinery, where a periodic excitation is caused by unbalance forces. As a consequence, a control force cannot be added to the excitation directly. Instead, one typically uses active magnetic bearings (AMBs) that allow the application of forces to the shaft of a rotor. Our electromagnetic actuators mounted to both sides of the tip mass are a primitive realization of AMBs. While AMBs can apply large attracting and repelling forces over larger distances, our actuators can only exert attracting forces and have a rather small range of effect of approximately 2mm. Furthermore, the applied force depends non-linearly on the width of the gap between tip mass and magnet, and on the control-signal voltage, which makes our actuation system non-linear and state-dependent. An important question of interest was, if, and under which conditions, such an actuation system is suitable for constructing a non-invasive stabilizing control scheme required for applying control-based continuation [4].

Algorithmic challenges

Two obvious problems that need to be addressed by a toolbox for continuation in experiments are measurement noise and time. In the language of COCO [3], the presence of noise necessitates the implementation of suitable atlas and curve segment classes, while measurement times of the order of seconds per function evaluation call for update methods for derivatives instead of the application of finite difference methods used by default. Besides these two fundamental problems we observed a surprisingly large number of mostly unanticipated algorithmic challenges when coupling our algorithms to our impact oscillator:

Non-linearity of control system. Although expected, the non-linearity of the control system posed a serious problem, which was eventually solved by the development of a control tuning algorithm [5].

Resonances. Resonances of the pendulum with the shaker sub-system lead to a quite rich bifurcation structure, for example, small hysteresis loops with a size comparable to measurement noise. As consequences, we observed sudden and localized changes of variance in measurements, large jumps of the continuation method, double covering of the solution manifold, and failure of the default method of step-size control. Each of these problems was so severe that only about 10-20% of executed continuation runs were successful until we finally managed to find solutions to all of these issues.

Balancing of equations. To address phenomena caused by resonance we use non-linear arc-length conditions. The residuum of any such condition competes with the allowed residuum in the experiment, because both residues are combined in the stopping criterion of the corrector. This caused significant convergence problems in the correction method and was solved by using a pull-back algorithm that ensures zero residuum in the projection condition.

Drift of parameters. The least expected but highly relevant problem is the drift of environmental parameters during correction. Some parts of the bifurcation diagram of our test rig are so sensitive to changes in environmental parameters (we suspect temperature) that the solution manifold can slowly drift out of the trust region of our corrector during correction. When this happens, it is impossible to resume continuation. The solution to this problem was the implementation of statistical tests in the corrector algorithm, which will detect a likely failure of the correction step as fast as possible to allow restarting the correction step with changed settings while the drift is still small.

Once we discovered and addressed all these phenomena, the success rate of CONTINEX on our test rig was increased to above 95%. In addition, a parameter sweep with comparable accuracy will take approximately the same amount of time as a continuation run, which implies that continuation with CONTINEX does not only provide more information than, but is also competitive with the execution time of a sweep.

The toolbox CONTINEX

A generic algorithm for evaluating a zero problem $F(x, p)$ corresponding to an experiment, a simulation, or an equation-free model, where x represents a target solution and p are the problem parameters, is: (1) Set problem parameters to p and reference solution to x. (2) Wait for transients to settle. (3) Read frame with data. (4) Compute and return residuum. Since this four-step algorithm is so general, CONTINEX provides a base class with four abstract methods corresponding to the steps above as an interface to an experiment or model. A user of CONTINEX is only required to to derive a problem specific sub-class from this base class and overload the four abstract methods. More specialized base classes with additional functionality are available for DSPACE, SIMULINK and ODE models. Once this sub-class is implemented, an instance of it together with initial values for the reference solution and parameters is passed to the toolbox constructor to initiate a continuation run. The CONTINEX specific atlas, curve segment and corrector algorithms are selected automatically by our toolbox.

Acknowledgements

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